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14. ABSTRACT OptiPro demonstrated the polishing and measurement of a glass tangent ogive using their previously developed belt polishing equipment and their latest UltraSurf measuring equipment. The surface roughness of the new splice-less belts showed a 8 to 9 Angstrom surface roughness. New tool path options were also demonstrated that compensate for radial and angle errors during polishing. Test ellipsoids were polished with the new tool path correction that improved surface accuracy from 5.23 micrometers peak to valley to 1.38 micrometers. The UltraSurf non-contact metrology system was used to measure the surface accuracy of a small convex dome and the surface accuracy and thickness of the as-ground ogive.					
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Recent Developments in the UltraForm Finishing and UltraSurf Measuring of Axisymmetric IR Domes

Mirror Technology SBIR/STTR Workshop

June 8, 2010

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INNOVATION

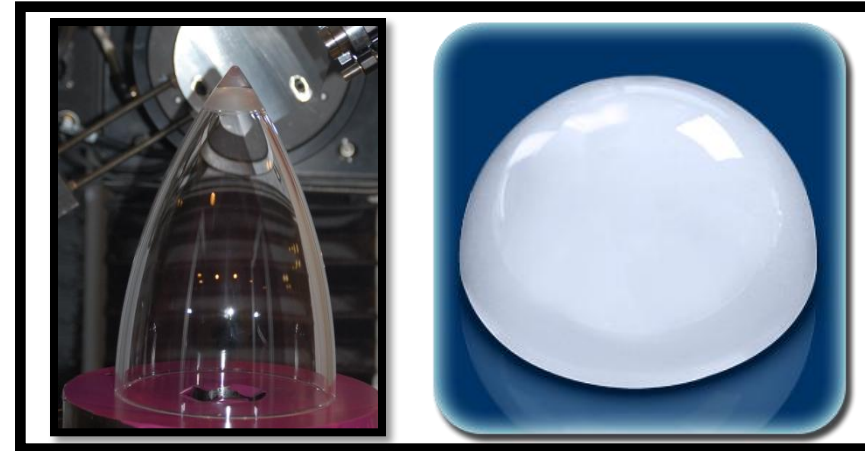
The UltraForm Finishing (UFF) and the UltraSurf platforms developed by OptiPro Systems deterministically polish and measure complex aerodynamic and conformal shapes made of difficult to manufacture glass, crystal and ceramic materials.

ACCOMPLISHMENTS

- ◆ 2008 OSA – Paul Forman “Excellence in Engineering Award” for first affordable Computer Controlled Optical Machining Center.
- ◆ Optical fabrication companies and prime contractor suppliers are embracing the new technology to cost effectively manufacture axisymmetric domes and optics for newly designed defense systems.
- ◆ The integration of the UFF (CNC controlled finishing platform) and the UltraSurf (Automated non-contact measurement device) provides a deterministic fabrication solution for a wide range of newly developed windows , domes and mirrors.

COMMERCIALIZATION

- ◆ UltraForm Finishing (UFF) : Asphere, Axisymmetric Dome , Freeform Polisher
 - Private Sector installations at Universities, Material manufacturers and Precision optical component manufacturers
 - US Patent No. 7,662,024 B2 : “Method and Apparatus for precision polishing of Optical Components”
- ◆ UltraSurf : Non-Contact Asphere, Axisymmetric Dome measurement platform
 - Private Sector Asphere and Dome Measurement System will be available by July 2010
- ◆ Primary market focus is on companies engaging in the optical fabrication and measurement of spherical domes, aspheres, parabolic mirrors, torics and conformal/freeform shapes.
- ◆ Private sector investment into the UFF and UltraSurf platforms has been through Beta site partners and production level machine purchases.
- ◆ OptiPro Systems, LLC has alliances with material manufacturing firms who require new manufacturing techniques to test and enhance their prototype components and determine the pathway to production level quantities.



Tangent Ogive and Spherical Domes

GOVERNMENT/SCIENCE APPLICATIONS

- ◆ Contract Numbers W31P4Q-05-C-R048 and W31P4Q-04-C-R101 awarded by the Defense Advanced Research Projects agency (DARPA); and Contract Numbers N68936-10-C-0094 and N68936-08-C-0050 awarded by the Navy Engineering Logistics Office and NAVAIR.
- ◆ Toric , Acylinder and other freeform/conformal geometric shapes made from Si and SiC are potential applications.
- ◆ Fabrication methods: Corrective Optics for Conformal Windows and Domes , NAVAIR Contract N68936-09-C-0016.
- ◆ OptiPro's deterministic fabrication and metrology solutions result in dramatic cost savings due to cycle time reductions and improved surface qualities.
- ◆ Materials Include : Spinel, ALON™, CeraLumina™ , Si, SiC, ceramics & standard optical glasses

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Optical Fabrication History

- **SX Optical CNC Machining Centers**
 - Defense Advanced Research Projects Agency, DARPA
 - Developed with the Center for Optics Manufacturing, Kodak and DARPA
 - Machines sold to fabrication companies and DOD Prime Contractors
- **ePX Spherical High Speed Optical Dome Polisher**
 - High Speed Polishing of JAGM Spinel and ALON Domes
 - Machines sold to fabrication companies and DOD Prime Contractor vendors
- **UFF UltraForm Finishing 5-Axis Polisher**
 - Initial prototype developed with Army Contract DAAE30-95-C-0091 SBIR
 - CeraLumina (PCA) Ogive production with Navy Contract **N68936-08-C-0050** SBIR
 - Machines sold to fabrication companies and DOD Prime Contractor vendors
 - Materials include: Optical Glass, PCA, ALON, Spinel, Si, SiC, IR Material
 - Shapes include: Domes, Aspheres, Ogive, Non-Axisymmetric freeform
- **UltraSurf 5-Axis Non Contact Metrology System**
 - Development with Naval Air Systems Command Contract N68936-07-C-0046 SBIR
 - Prototype platform for Dome, Ogive, Asphere and Freeform/Conformal surfaces

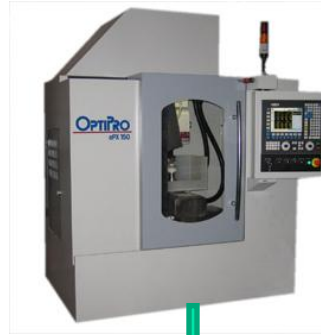


CNC Fabrication Equipment

eSX



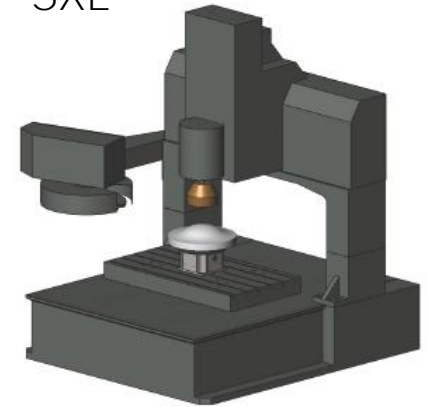
ePX



UFF



SXL



Large
UFF

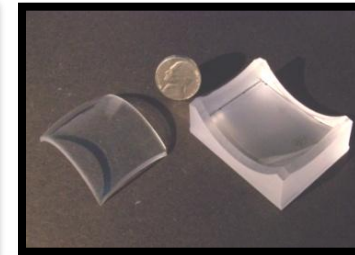
Dome



Ogive



Conformal





Materials

	CeraLumina™	Spinel	Sapphire	ALON™	SiC
Grain Size (microns)	0.4	100-200	2-5, 40-100	150-250	0.2 – 4.5
Hardness (Hv) Kgf/mm ²	2284	1350	1700	1560	2800
Fracture Toughness (K) MPa•m ^{1/2}	3.3	2.2	3.6	2.8	4.7

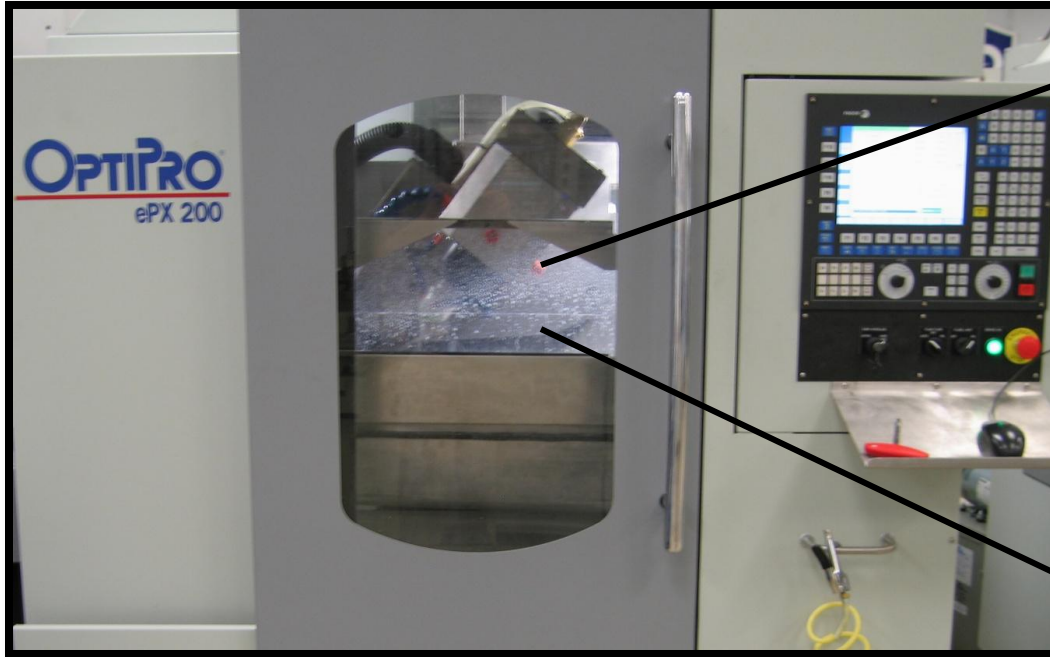
Standard Optical Material

- ULE & Zerodur
- Fused Quartz
- BK7 & Pyrex

Finishing Importance

- Transmissive and reflective surface wavefront
- Strength enhancement in brittle materials
- Contamination issues during coating

Dome High Speed Polishing Challenges

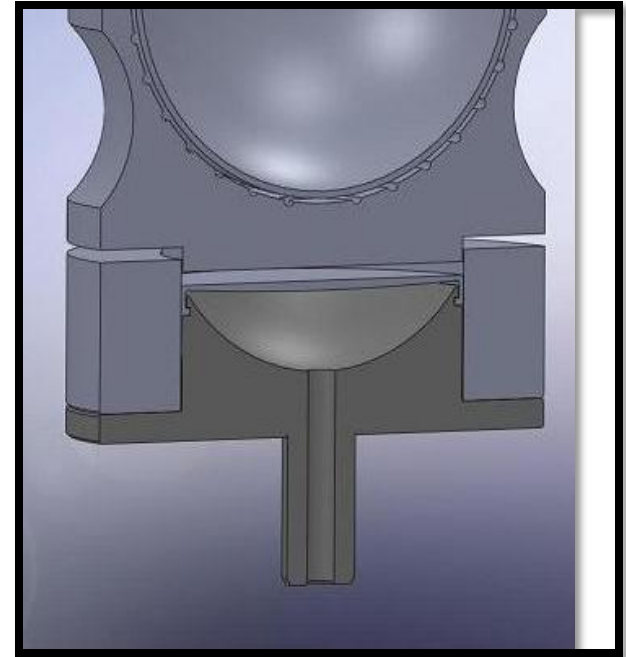
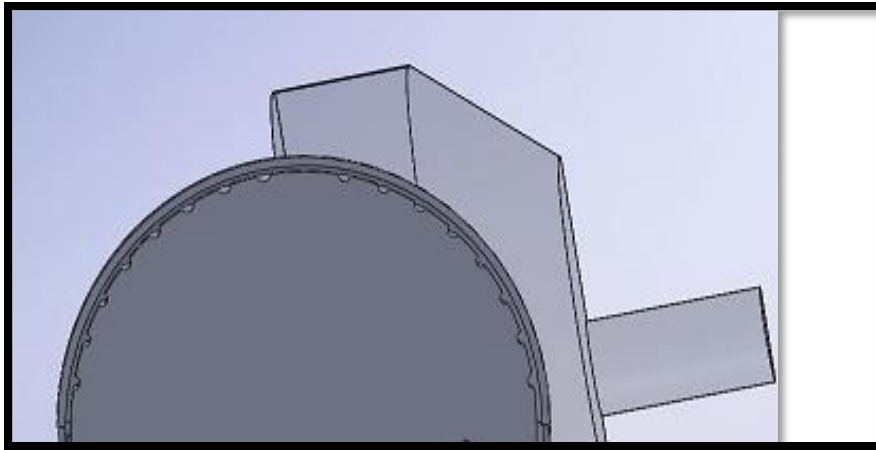


- Material removal & cycle time
- Grain highlighting
- Wavefront distortion
- Determinism
- Fixtures
- Spindle loads
- Tool Clearances
- 1:1 tool to part size



- High speed polishing platform
- Machine Features
 - High Torque Spindles
 - 1.3 Kw to 5.0 Kw
 - High Pressure thru the tool slurry
 - Tool Truing Process with variable toolpath & infeed
 - Work envelope optimized for dome process fixtures
 - Dome polish software customization
 - Easy Setup
 - User interface design with motion feedback & control
 - Work piece/Tool collision detection

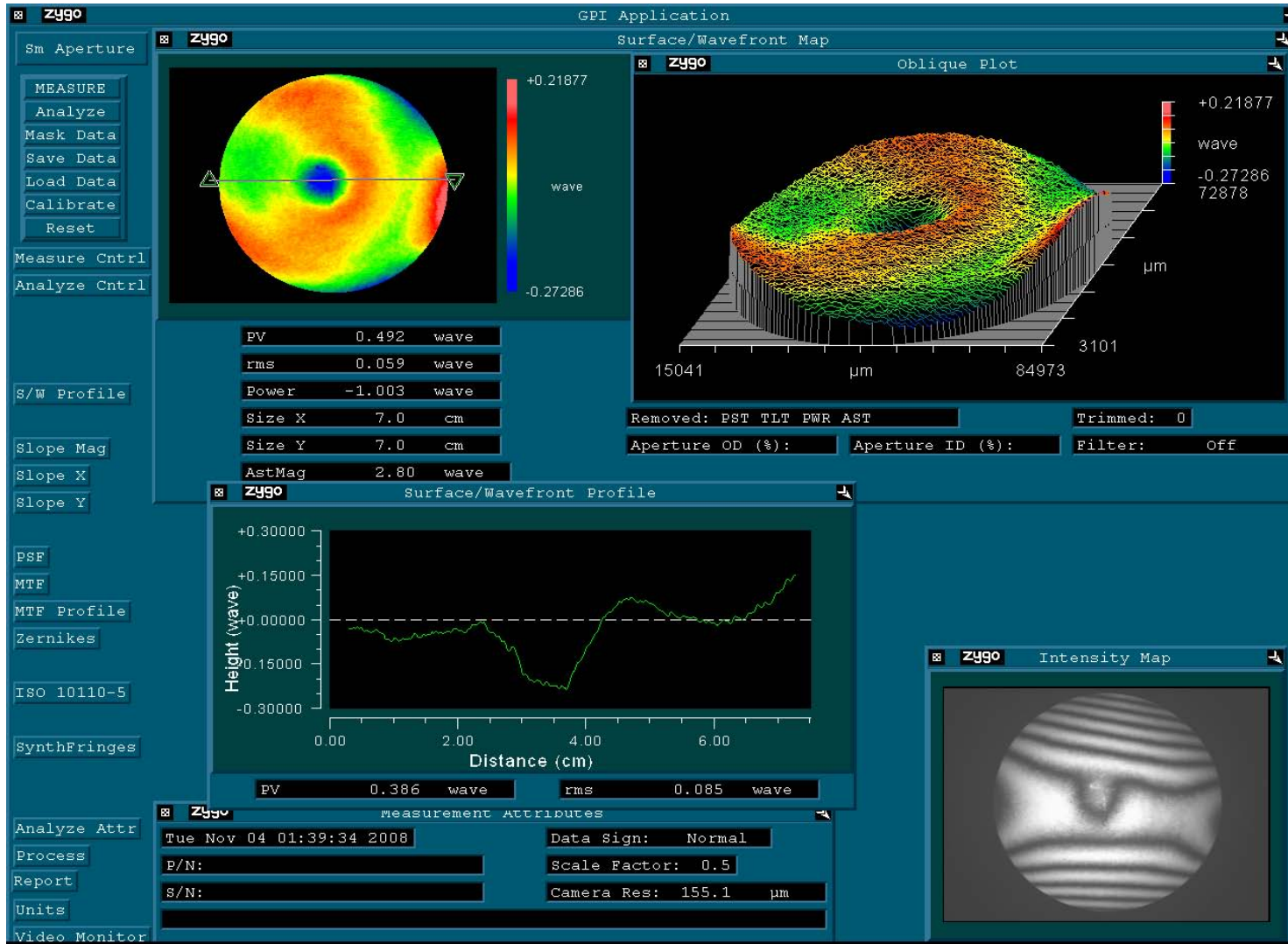
Hemi-Dome Fixtures



Polish grinding damage out of a 7" diameter dome
90-120min



Wavefront over 70mm aperture



2 mm thick
Dome

$\frac{1}{2}$ wave PV
.06 wave rms



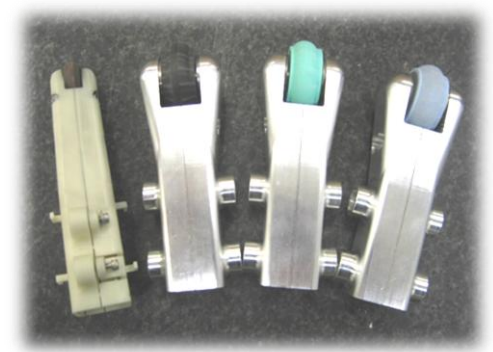
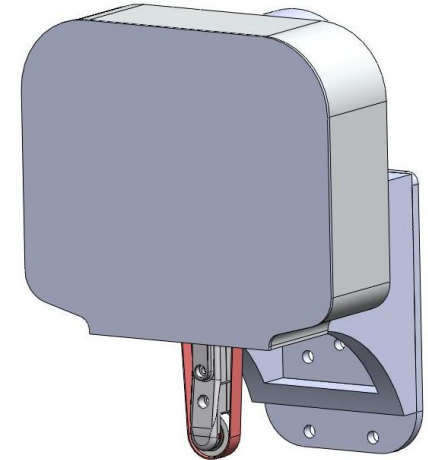
UltraForm Finishing



- 5 axis CNC Platform: 3 Linear X,Y,Z and 2 Rotary B and C
- Industrial Fagor 8070 CNC Control with User Friendly GUI
- On-Board metrology for removal function and preliminary part measurement
- Bound/Fixed abrasive with Coolant & Slurry containment - feed systems



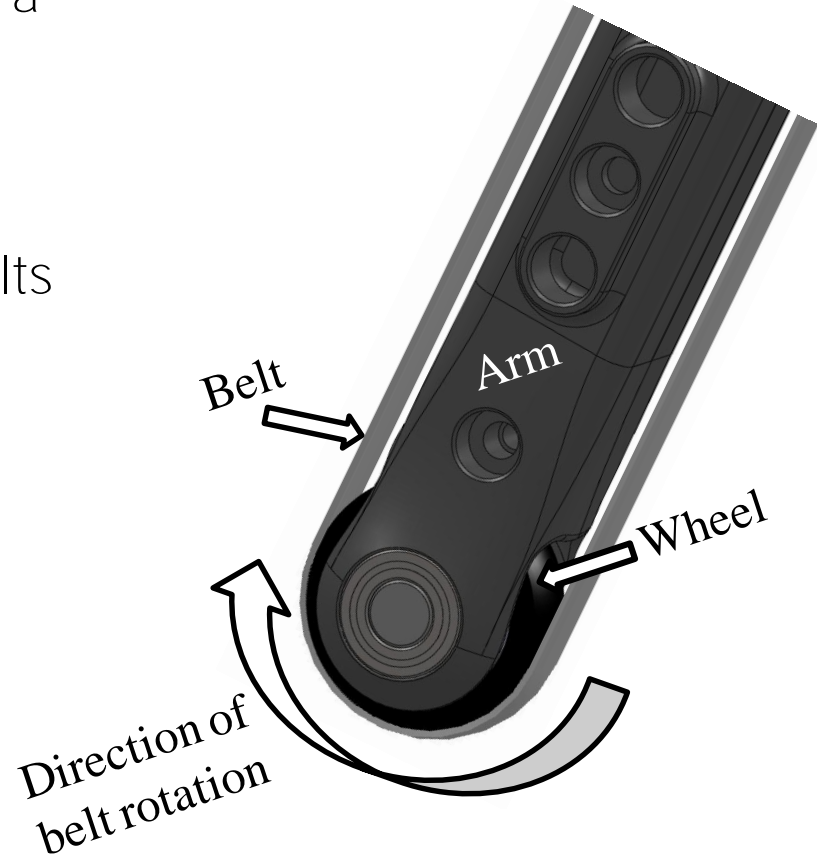
- Polish, fine ground spherical, aspheric, freeform and plano surfaces (No pre-polishing requirements)
- 2 different length arms, the long extension arm of the wheel allows finishing inside deep concave ogive missile domes
- Wide variety of Ultrawheel durometers and diameters and abrasive belts
- Long belt lengths with a variety of finishing materials and slurries allows for a more deterministic polishing process
- On-board metrology for work piece and removal function analysis
- Intuitive Graphical User Interface with surface correction algorithms





UltraForm Finishing: How it Works

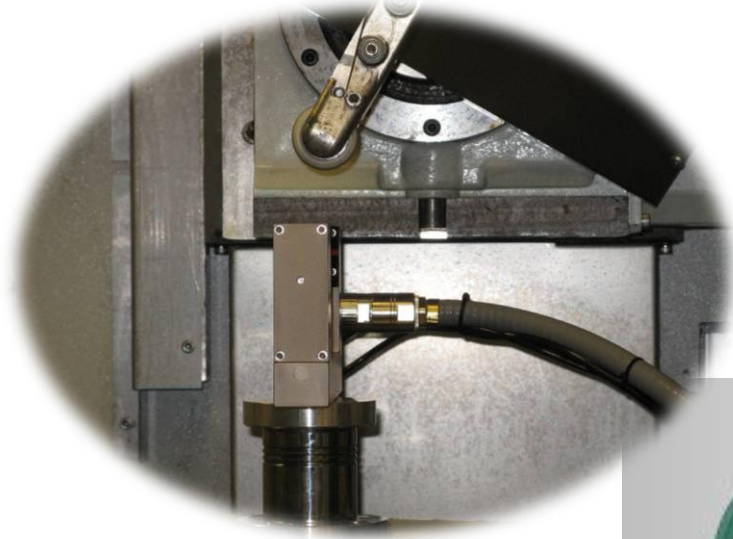
- UltraForm Finishing polishes using a precision controlled belt
- Fixed abrasive cerium oxide, alumina and diamond belts
- Conventional polyurethane pad belts with abrasive slurries



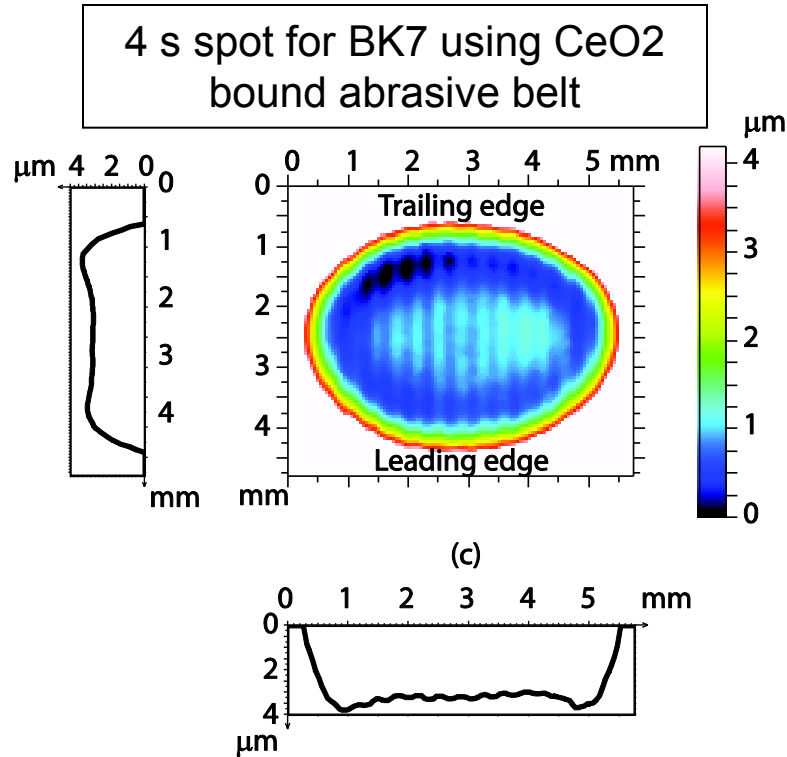


In-Situ UltraWheel geometric measurement

- Laser Probing the tool insures process repeatability
 - The exact location of the tool in the X and Y axis
 - This allows for the best possible centering
 - The exact size and shape of the tool
 - This allows for the tool to be modeled as accurately as possible

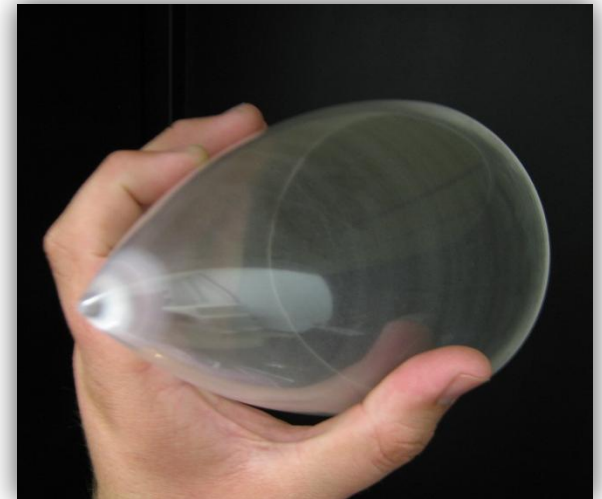


UFF removal function is measured in situ w/noncontact optical sensor



- Non-contact chromatic confocal imaging optical sensor (collimated white light) for 3D surface metrology
- Innovative non-contact technique for 3D metrology recommended by the **ISO 25178** international standard.

Glass Tangent Ogive 2009





Glass Tangent Ogive 2010



Rough and Fine Grind OD



Move Fixture with Ogive to
UltraForm Polishing
Machine

Glass Tangent Ogive



Fused Quartz Glass Ogive processed from solid block to expedite the work piece requirements for metrology tests

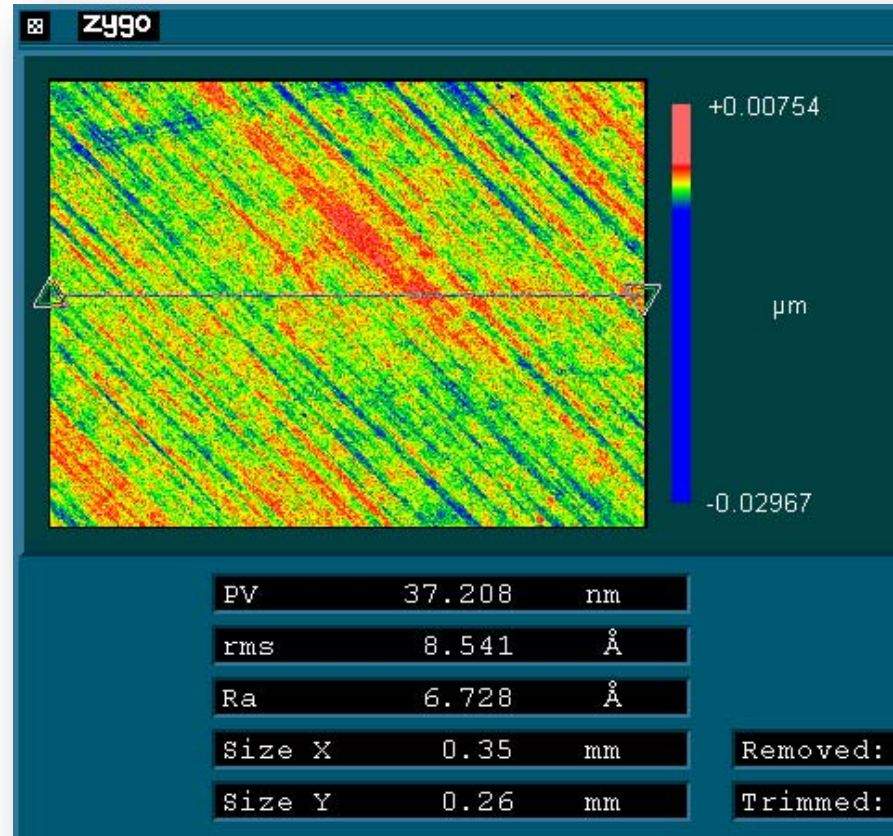


Recent Developments in UFF

- New Splice-less belt designs
- R-Theta error correction algorithm solution
- Conformal optics Ellipsoids, Toroids and Aspheric Cylinders using raster algorithm solution
- Cost reduction in production aspheres

Splice-less Belts

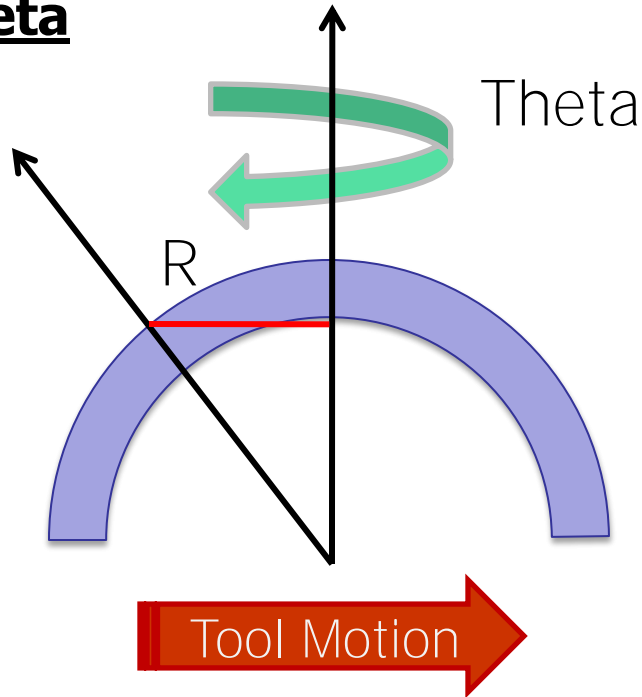
- BK7
- Spray on slurry
- 8-9 Å RMS surface roughness



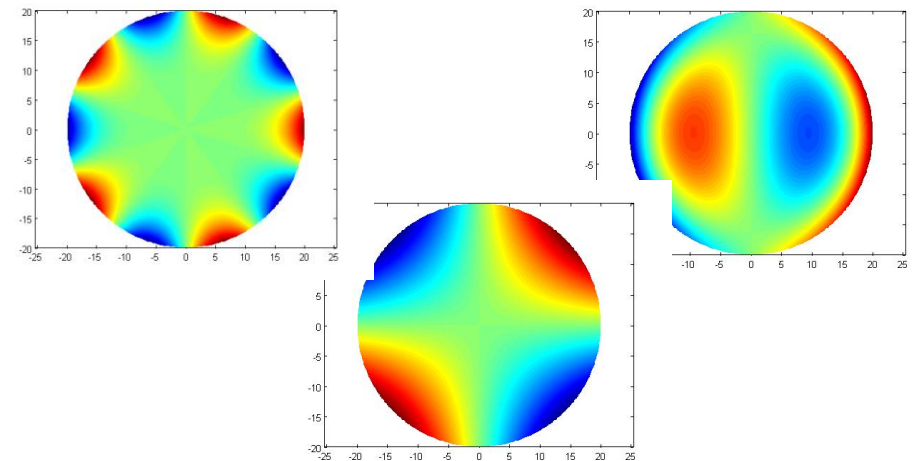
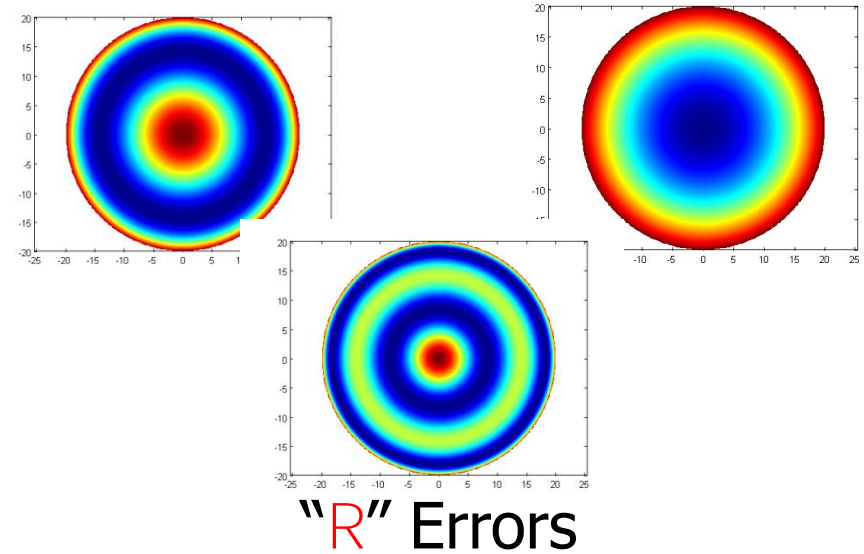


Tool Path Options includes “R” & “Theta” error corrections

R-Theta

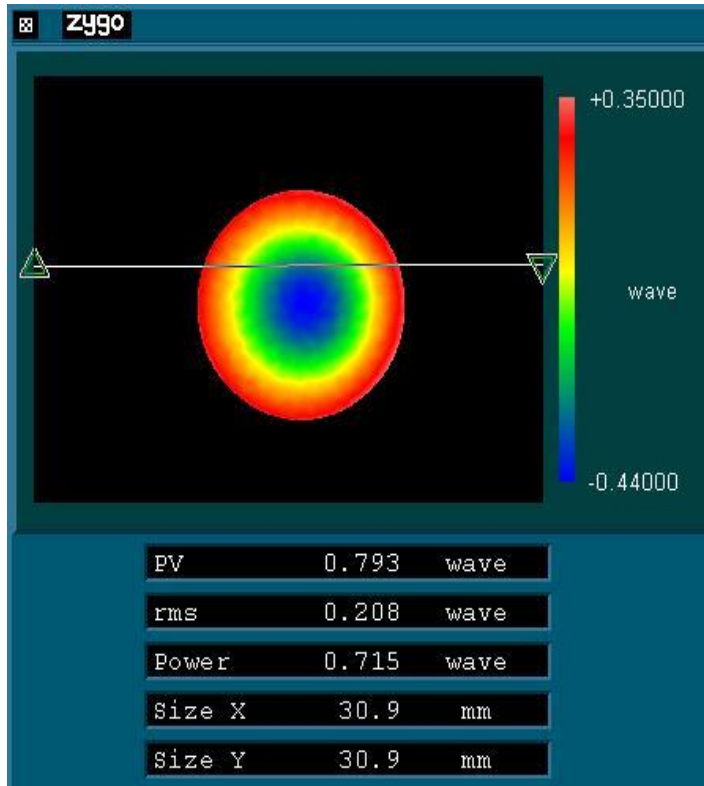


- Tool traverses left to right
- Best for rotationally symmetric shapes

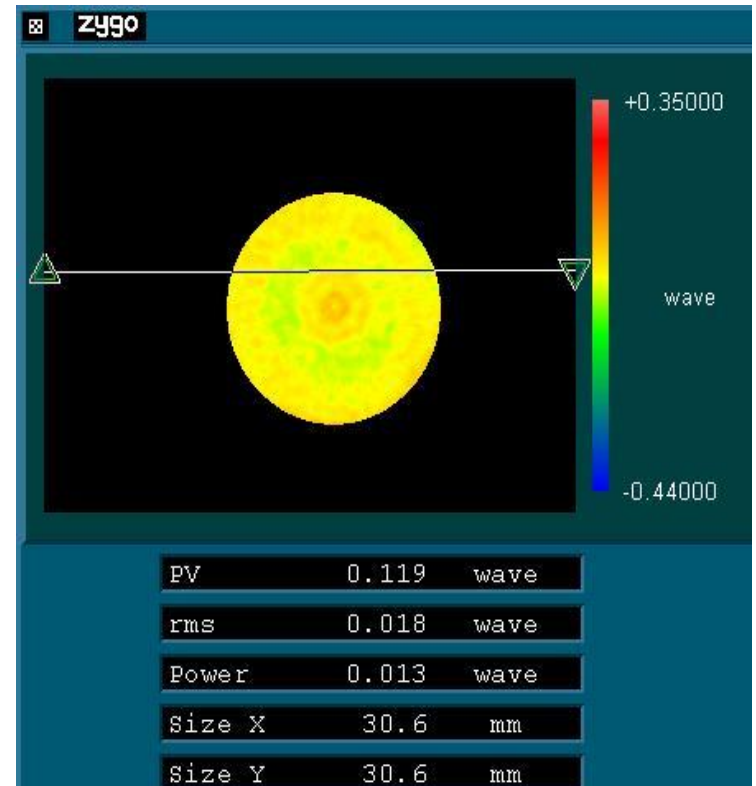


“Theta” Errors

R-Theta results example for BK7

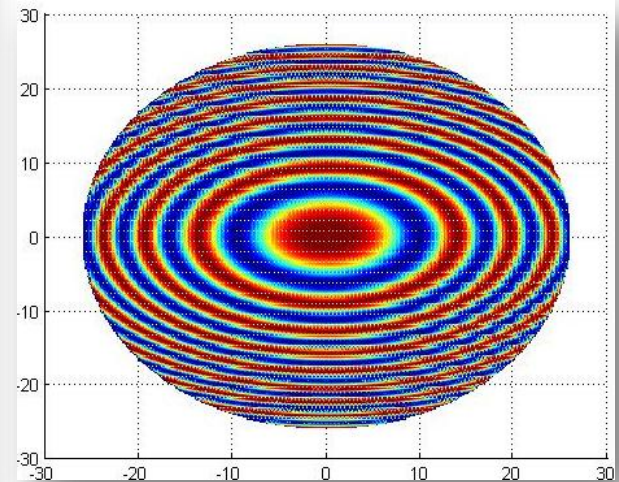
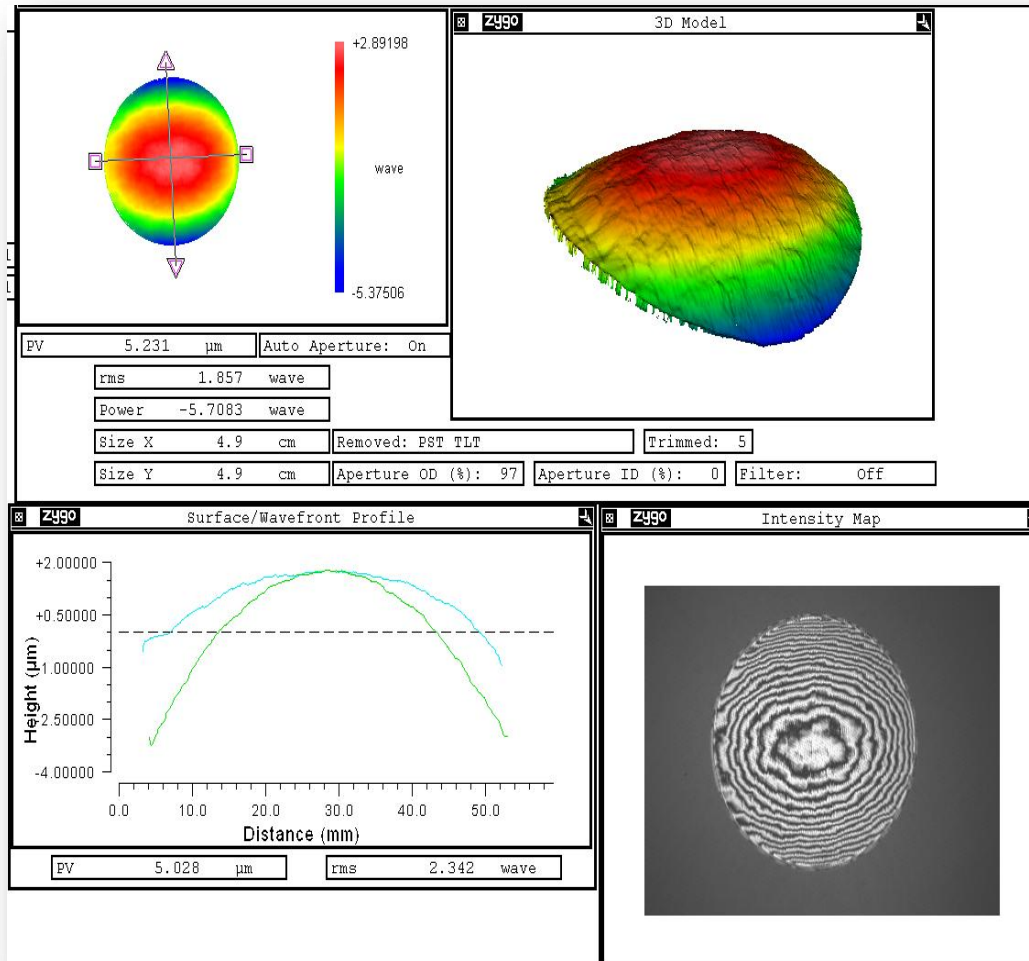


- Initial Surface
- PV: 0.793λ
- RMS: 0.208λ



- Final Surface
- PV: 0.119λ
- RMS: 0.018λ

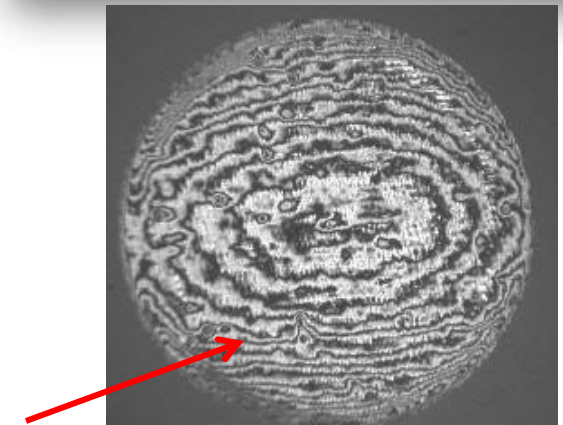
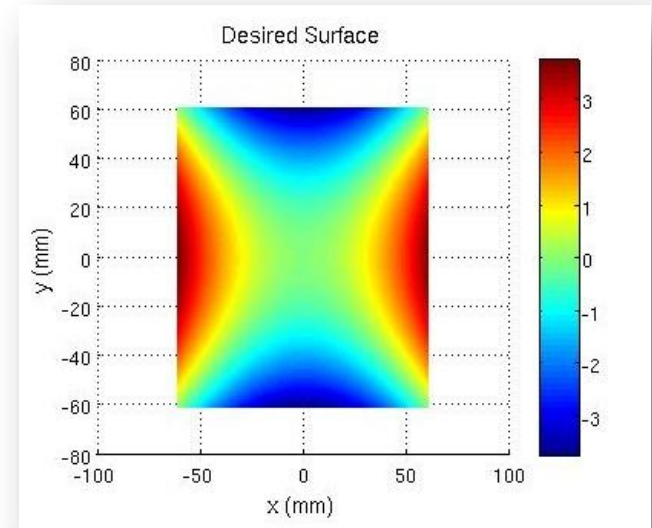
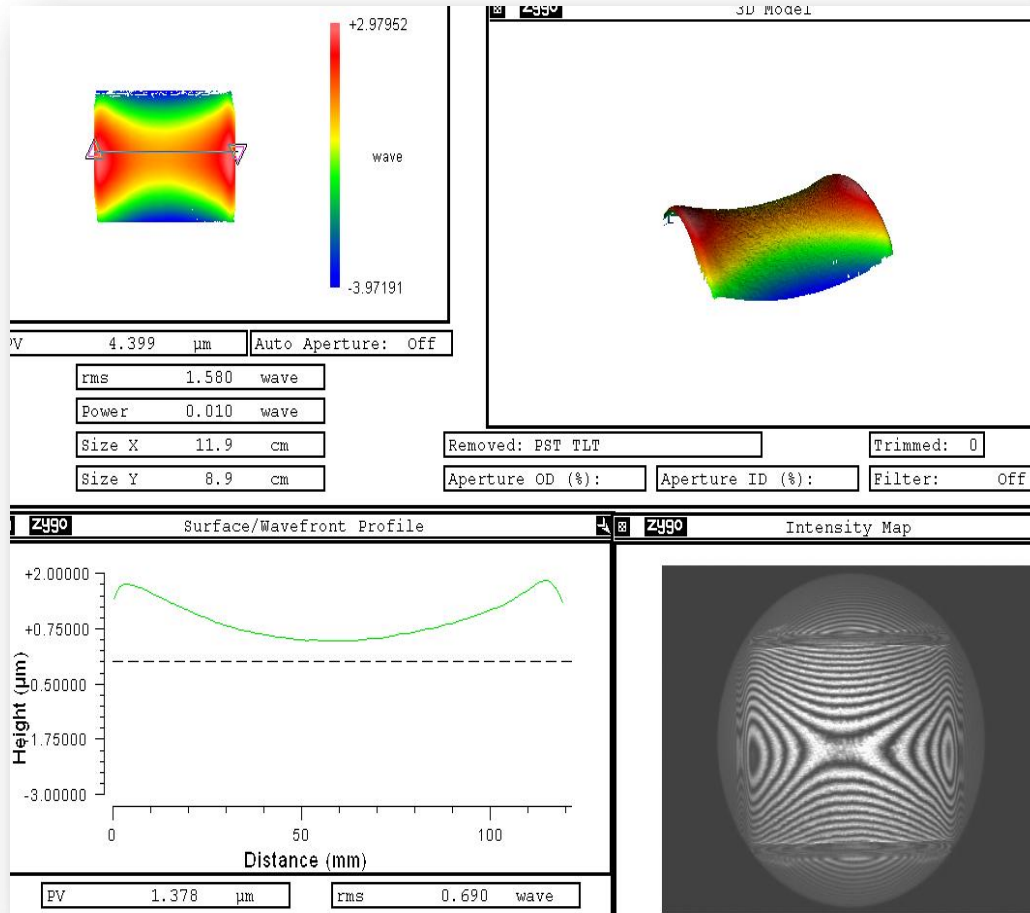
Results – Ellipse Raster 2009



Simulation: 5.1 μm

GPI PV: 5.23 μm

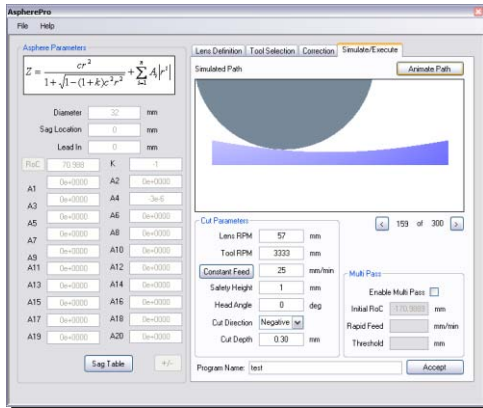
Results – Ellipsoid Raster 2010



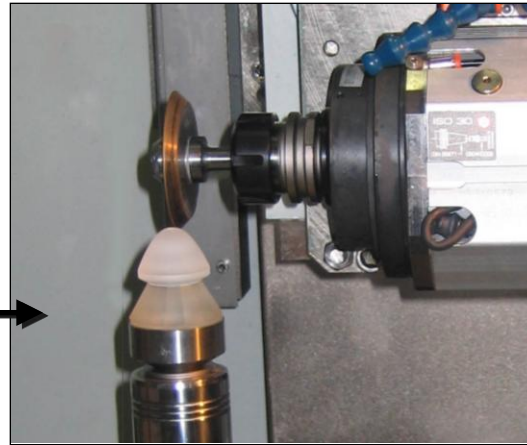
Ellipsoid From 2 Years Ago



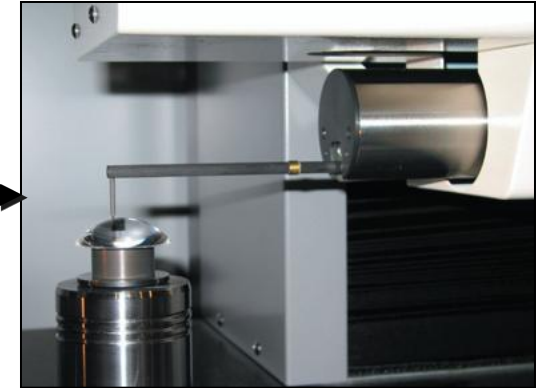
Cost Reduction in Production Aspheres



Define-AspherePro

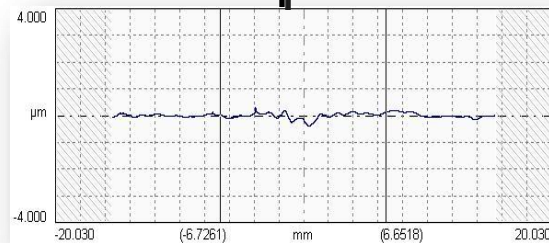
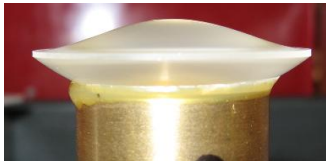


Grind-eSX or SXL 5 axes grinder

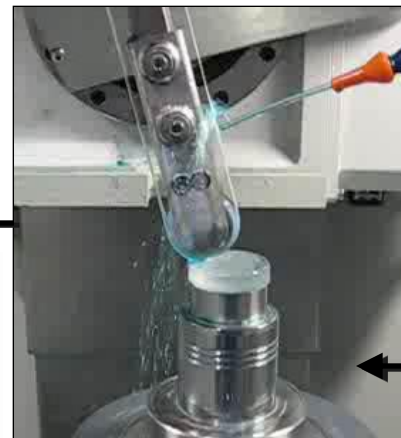


Measure-OptiTrace 5000

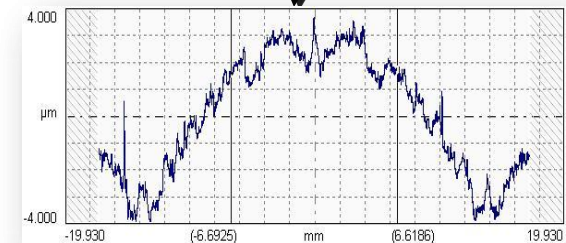
Finished Asphere



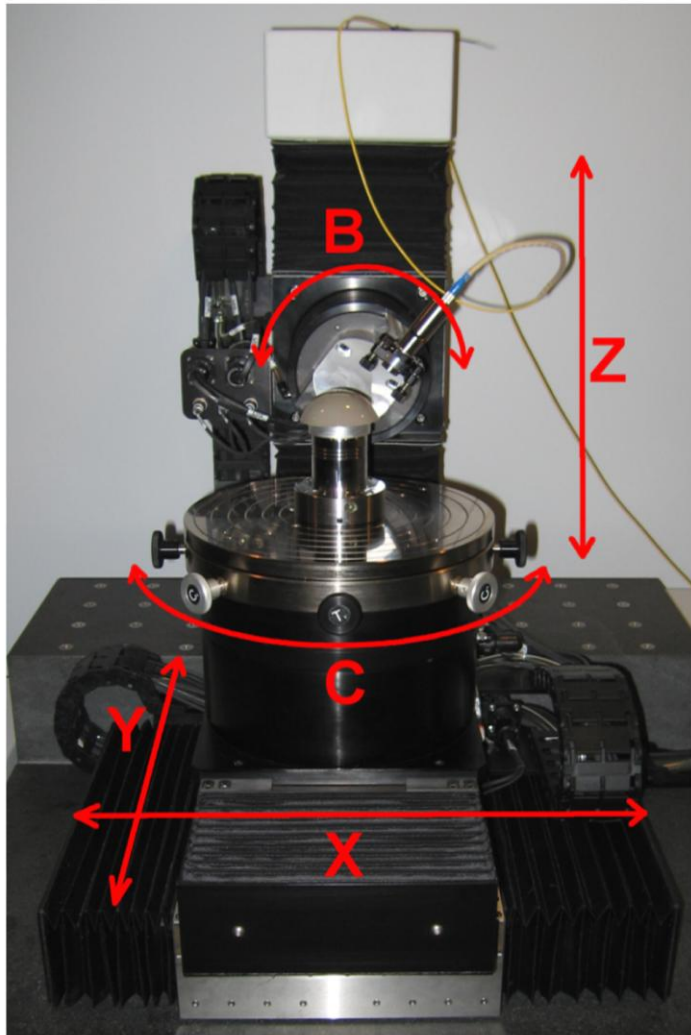
1-2 polishing iterations and ship!



Polish- UltraForm Finishing (UFF)



Transfer measured data to UFF

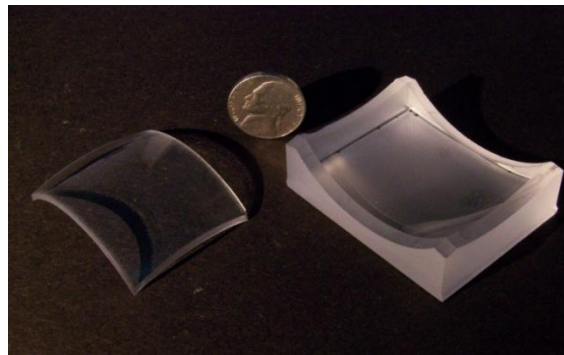
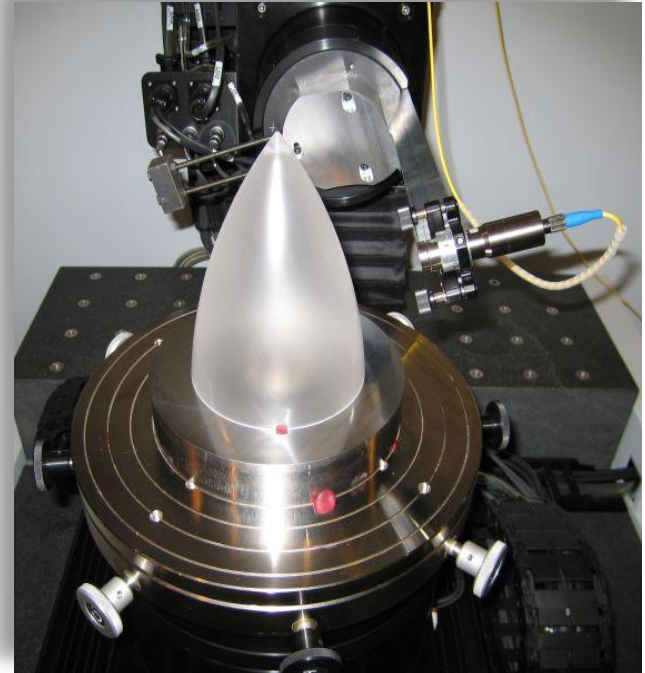
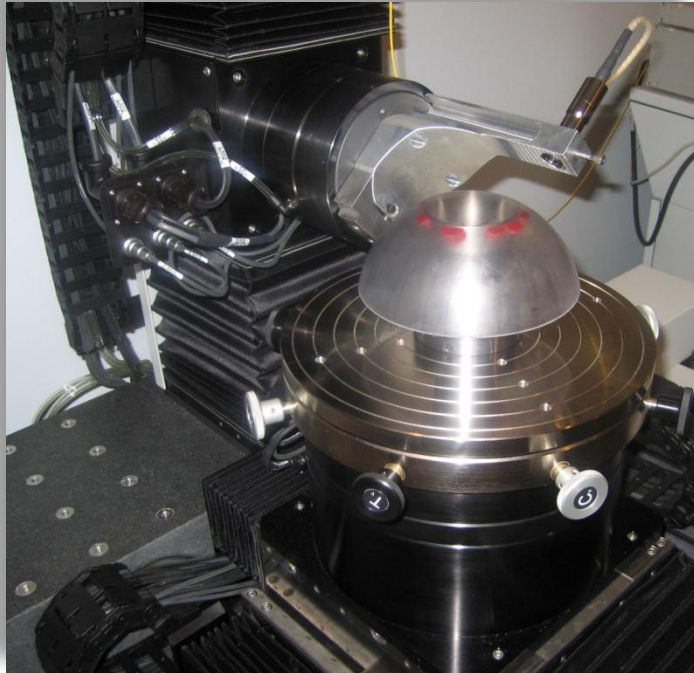


- 5-Axis Non-Contact Measuring System
- Utilizes Various Non-Contact Probes
- All Air Bearing Axes
- Linear Motors
- Brushless DC Rotary Motors

Axis:	X,Y,Z	B	C
Travel:	200 mm	360°	360°
Resolution:	5 nm	0.018 second	0.009 second
Accuracy:	25 nm	0.09 second	0.045 second
Max. Velocity:	30 mm/s	6 RPM	6 RPM

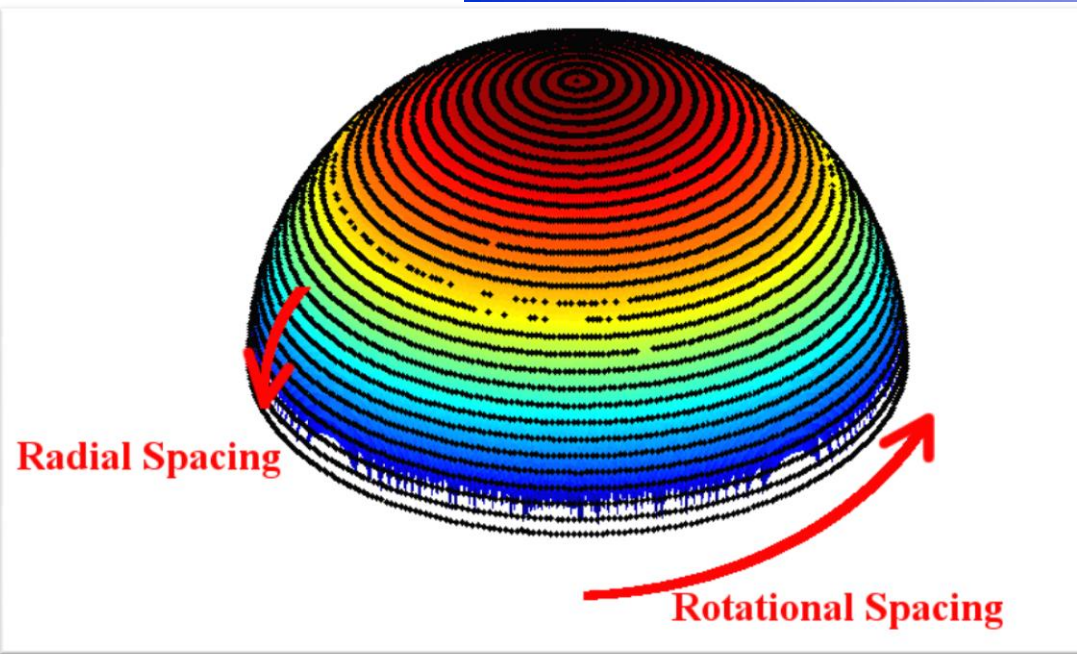


UltraSurf Dome, Ogive and Freeform



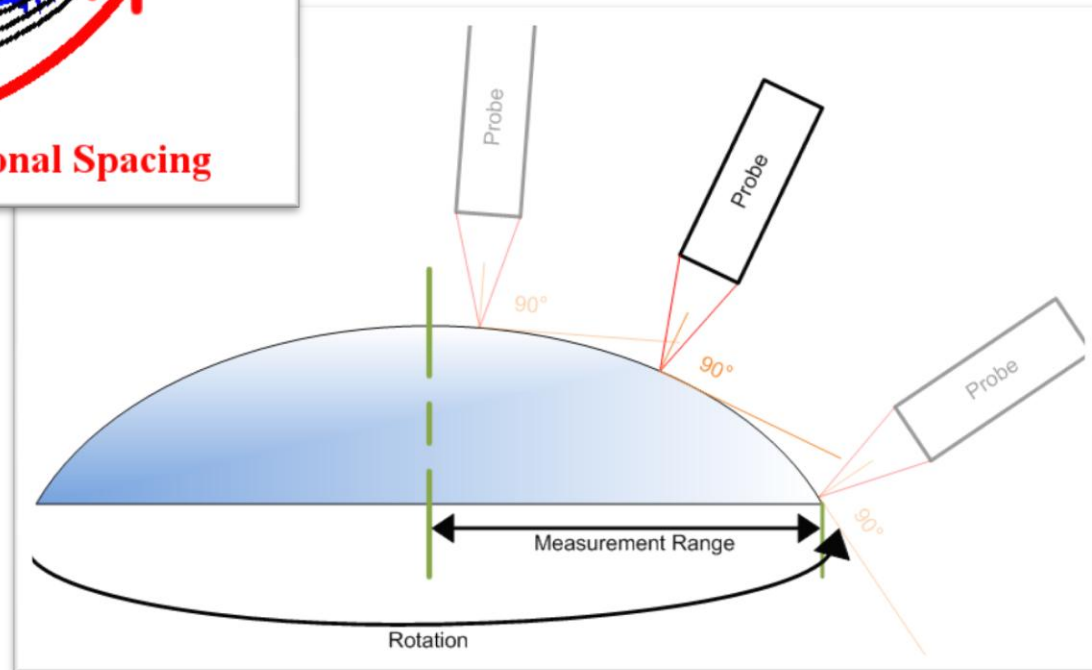


Typical UltraSurf Measurement



Concentric rings on a rotationally symmetric part

Spacing Can Be Dynamically Controlled



Optical Probes

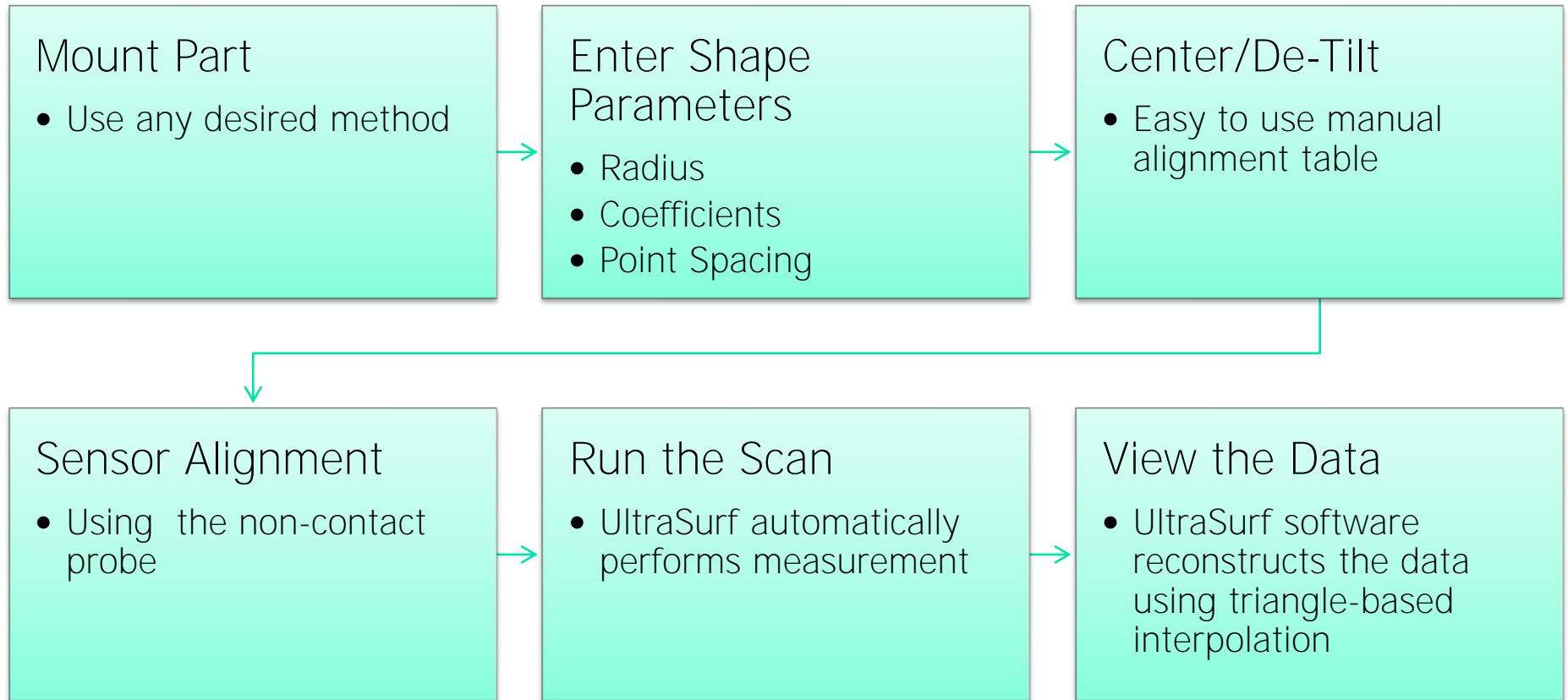


<u>Probe:</u>	Lumetrics OptiGauge	STIL OP300VM
<u>Measurement Range:</u>	12 μm – 15 mm	300 μm
<u>Focal Distance:</u>	25 mm or 50 mm	5 mm
<u>Focal Point Diameter:</u>	100 μm	10 μm
<u>Angular Tolerance:</u>	2 °	25 °
<u>Accuracy:</u>	200 nm	90 nm
<u>Resolution:</u>	30 nm	10 nm
<u>Scan Rate:</u>	1 - 50 Hz	50 - 2000 Hz

Currently testing and implementing these 2 non-contact probe styles.
Other probes may be utilized on the UltraSurf.

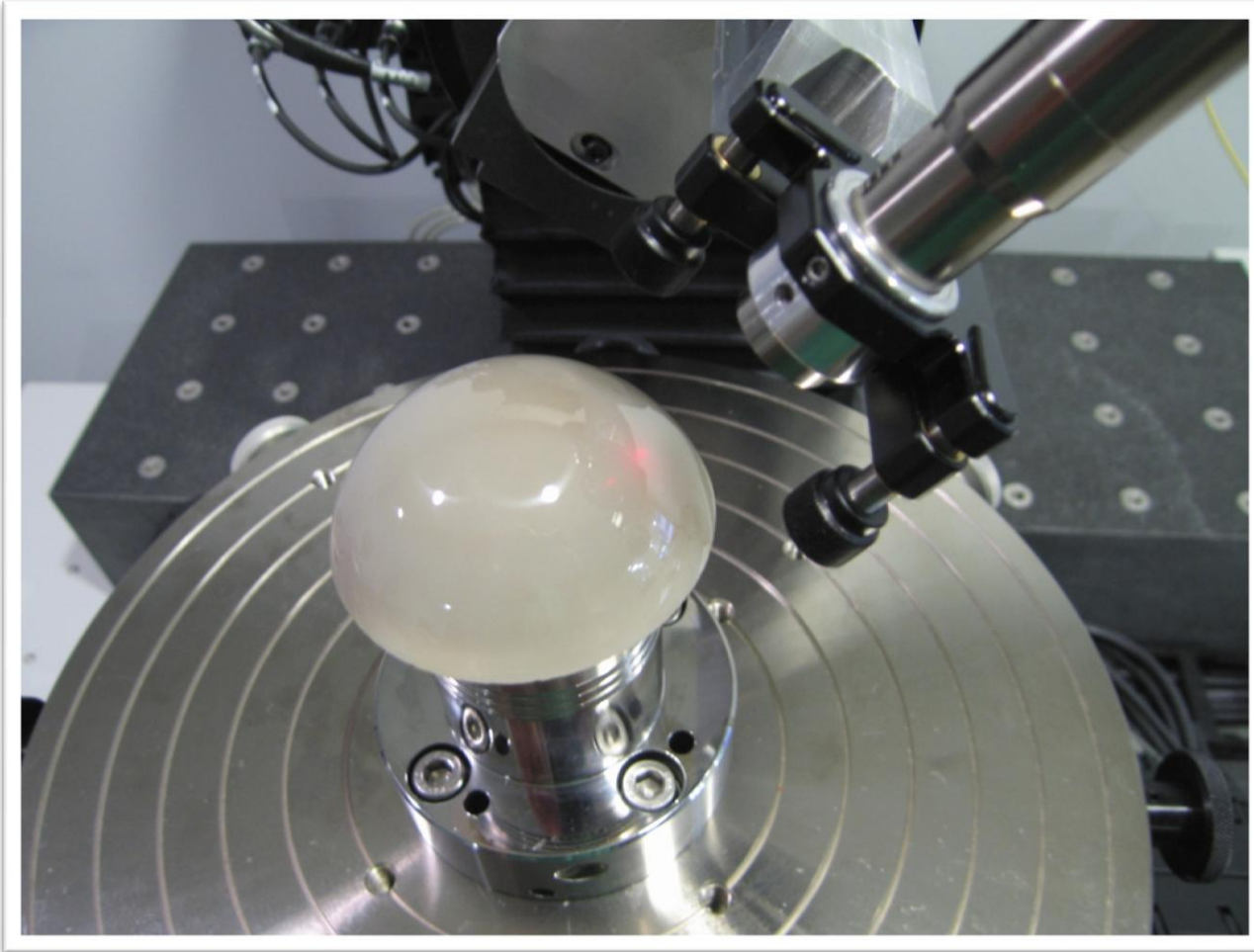


Process Flow For Measurement



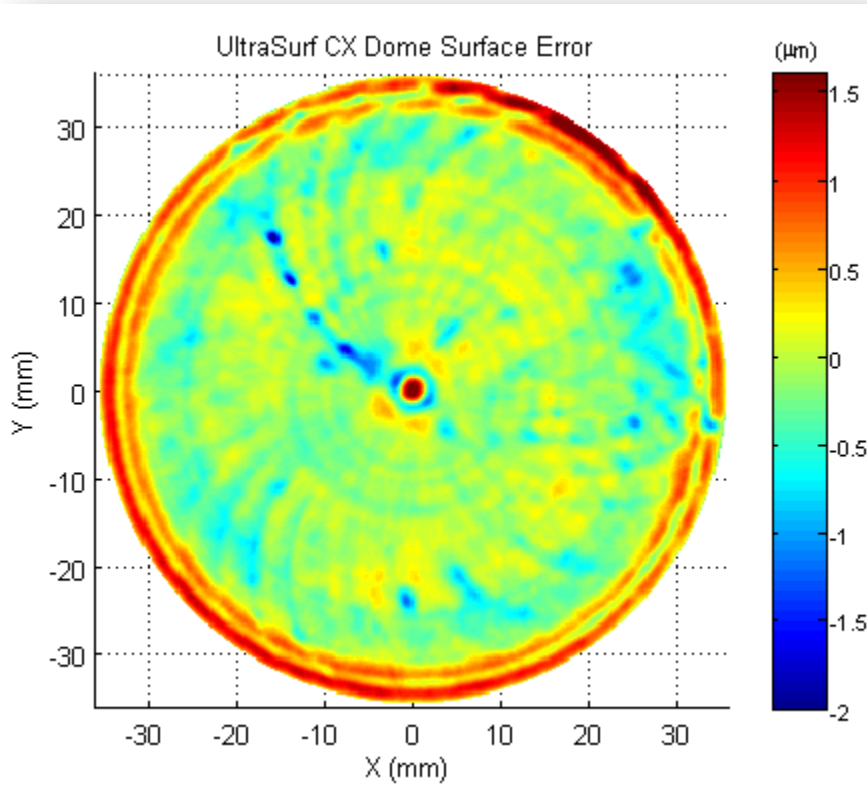


Small Dome Setup

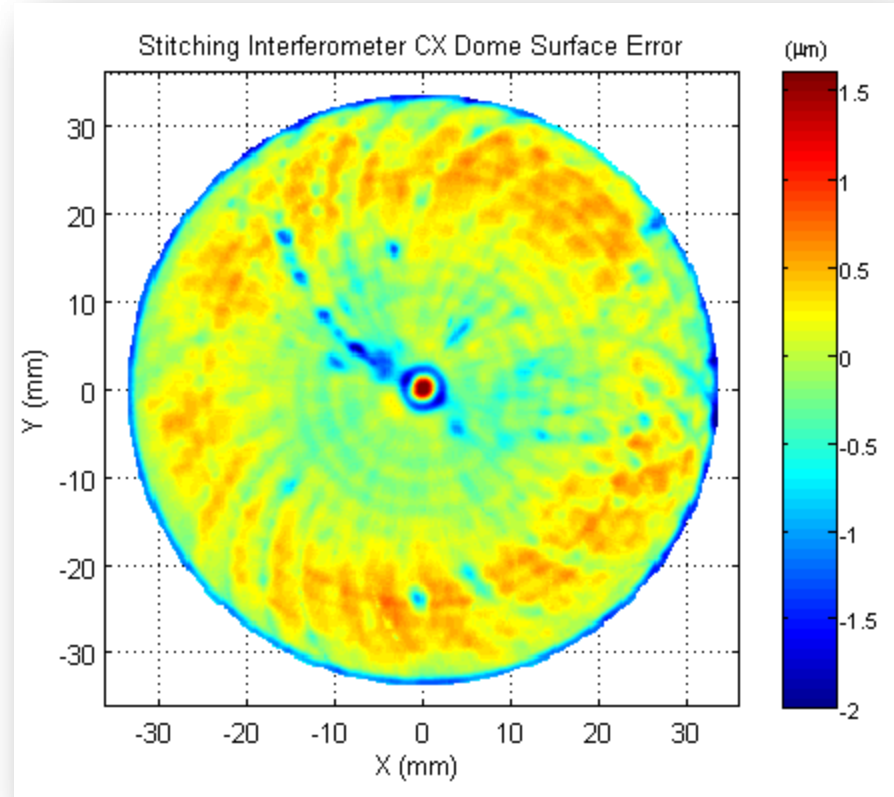


Small Dome, Convex Surface Error

UltraSurf

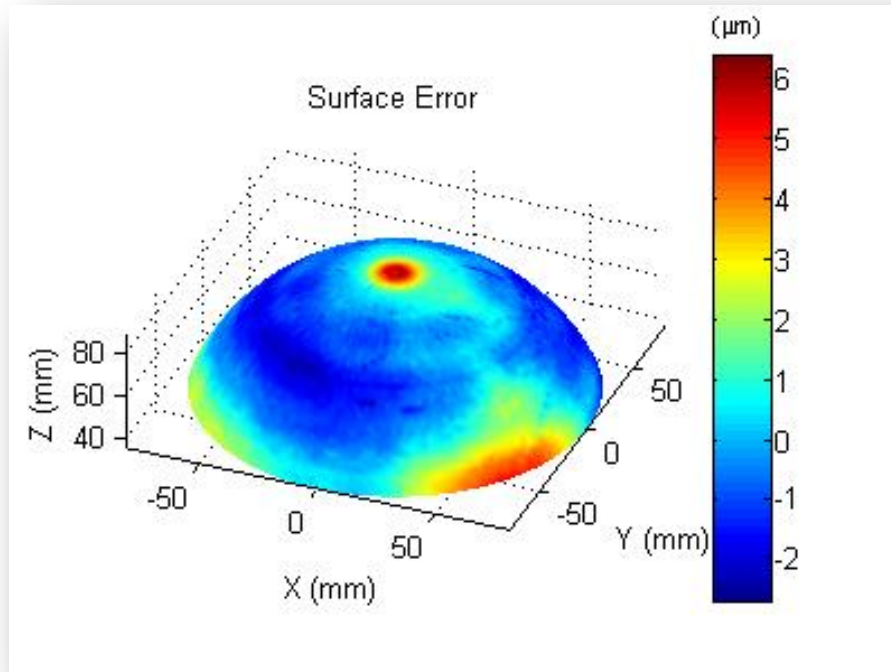


Stitching Interferometer

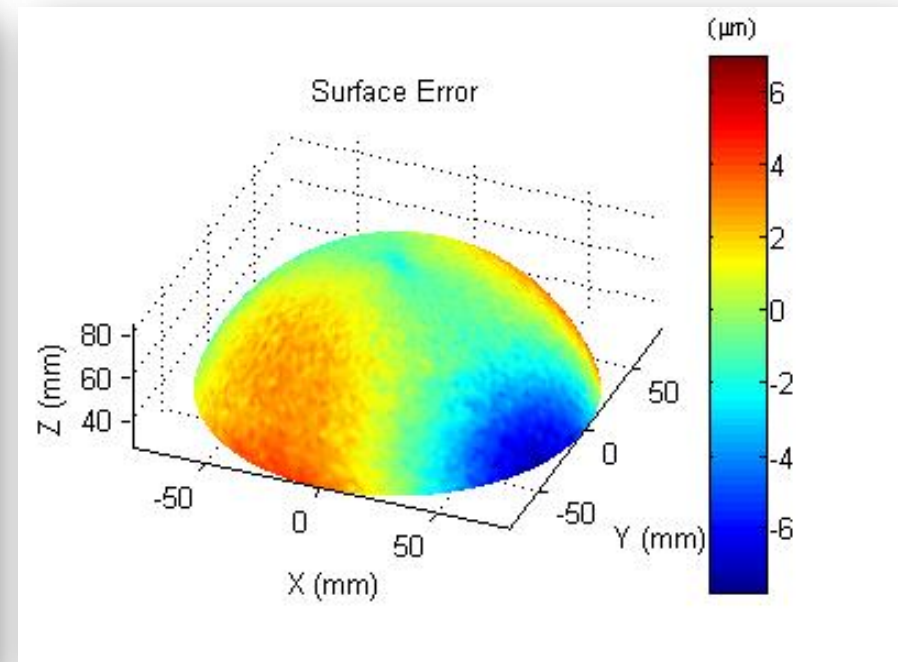


Large Dome, Surface Error

Convex



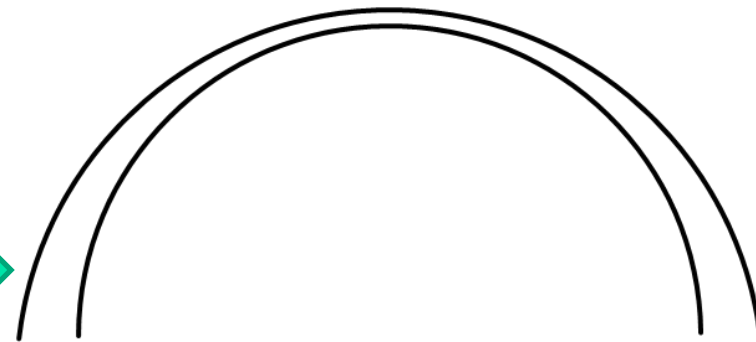
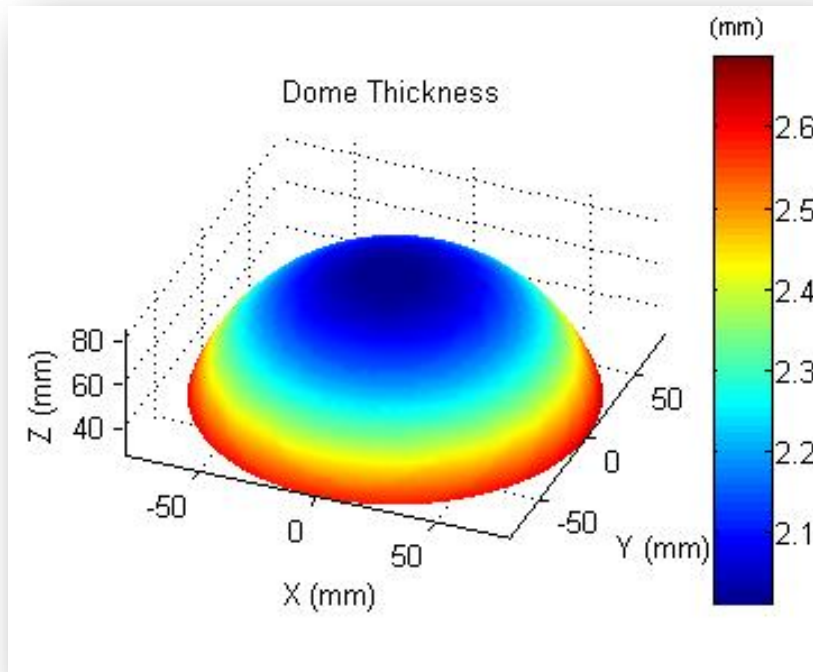
Concave



Surface Error Projected over Dome

Large Dome, Thickness

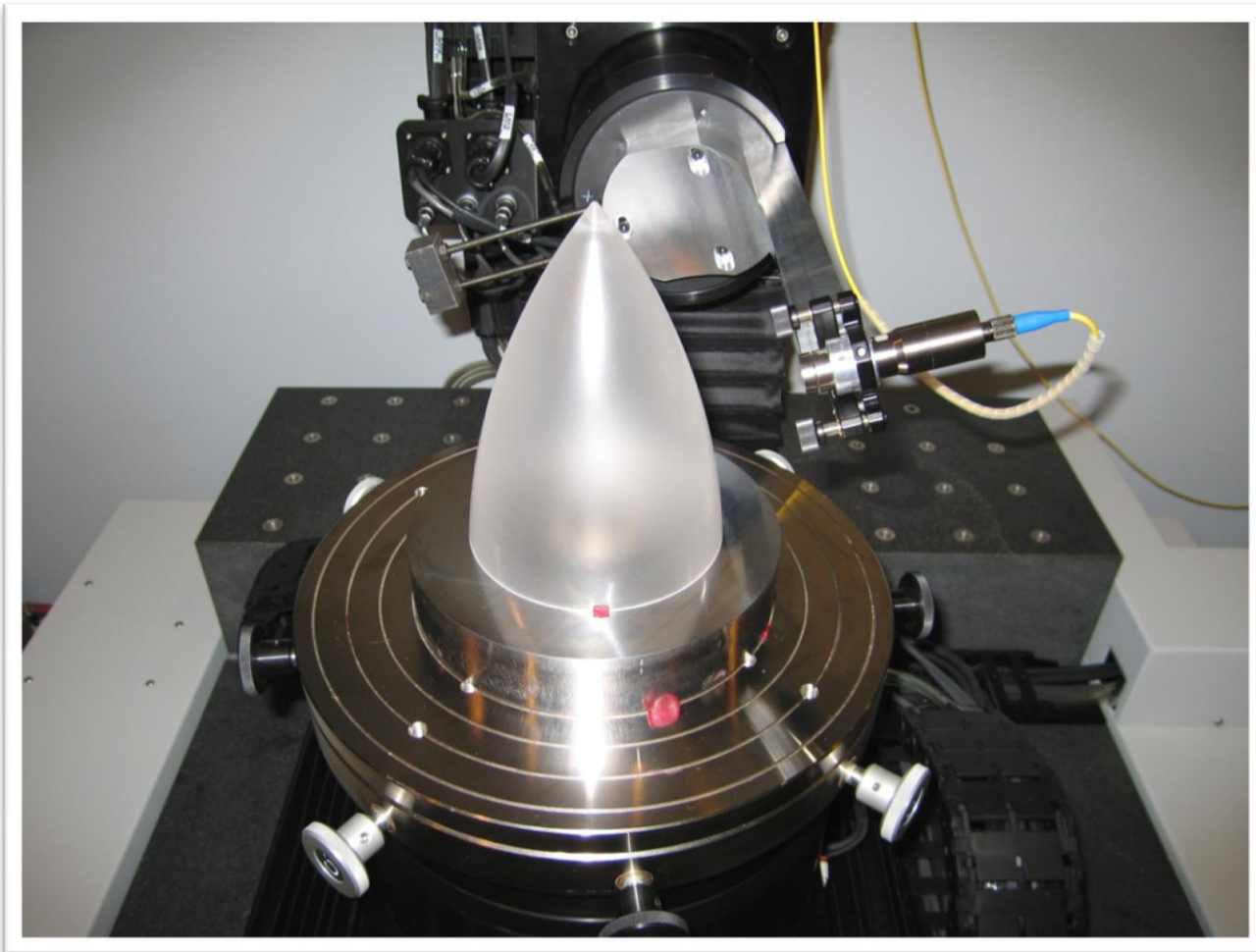
Overall Dome Thickness



Thin Center, Thick Edge

Curve Mismatch, 97 μm
Wedge or Piston

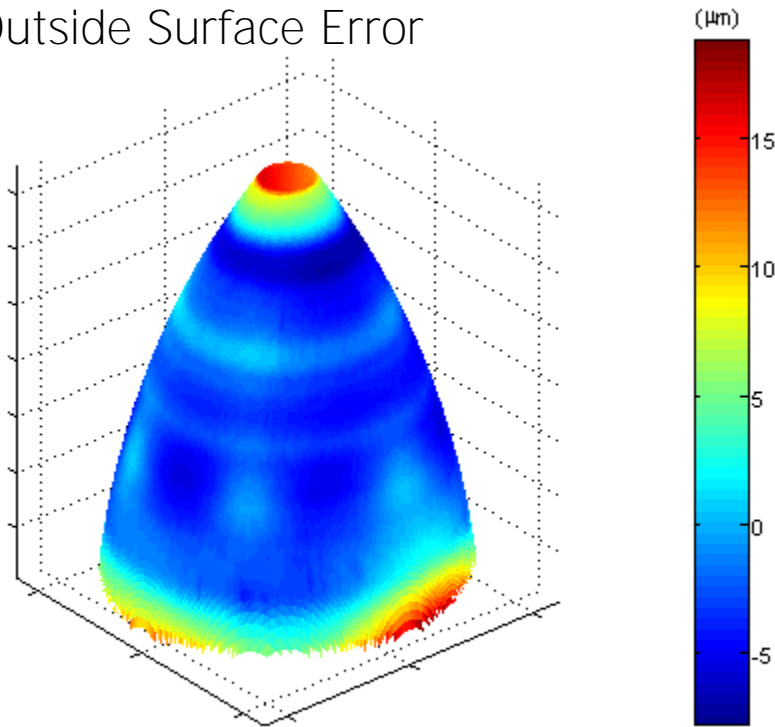
Ogive Results



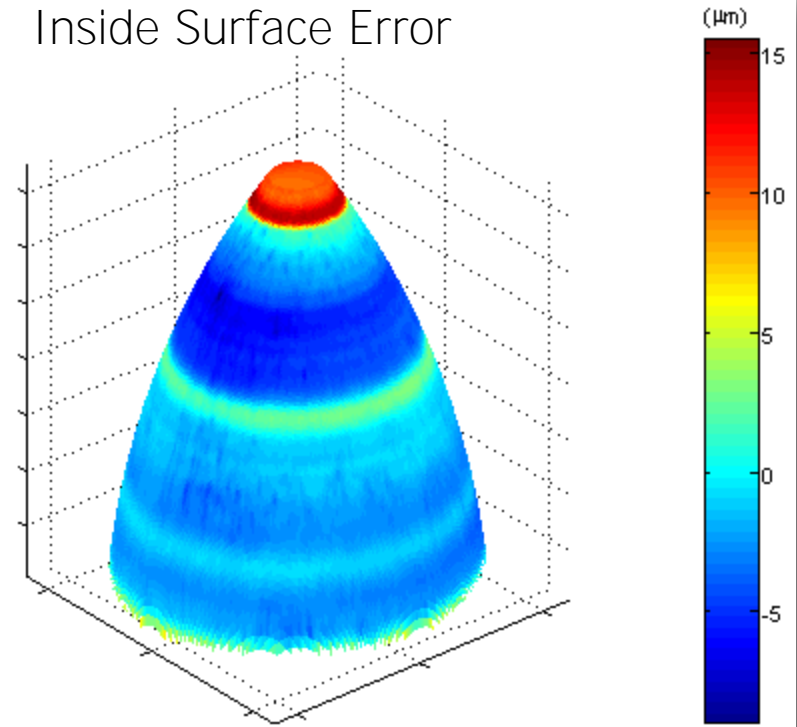
Large, Fine Ground Ogive

Ogive Surface Results

Outside Surface Error



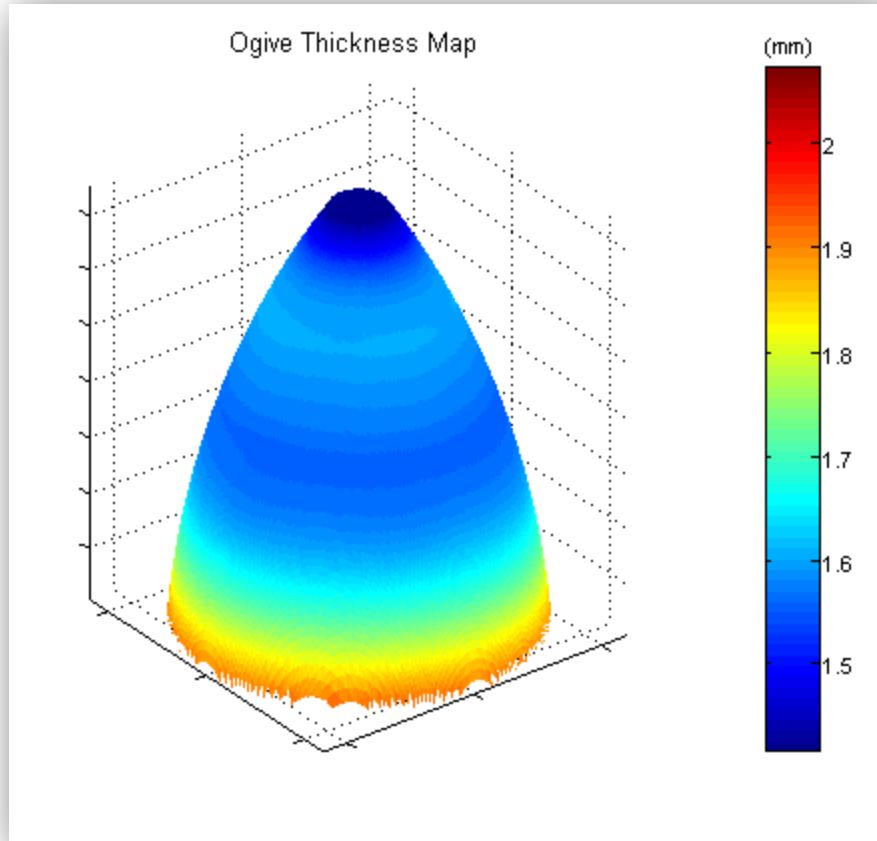
Inside Surface Error



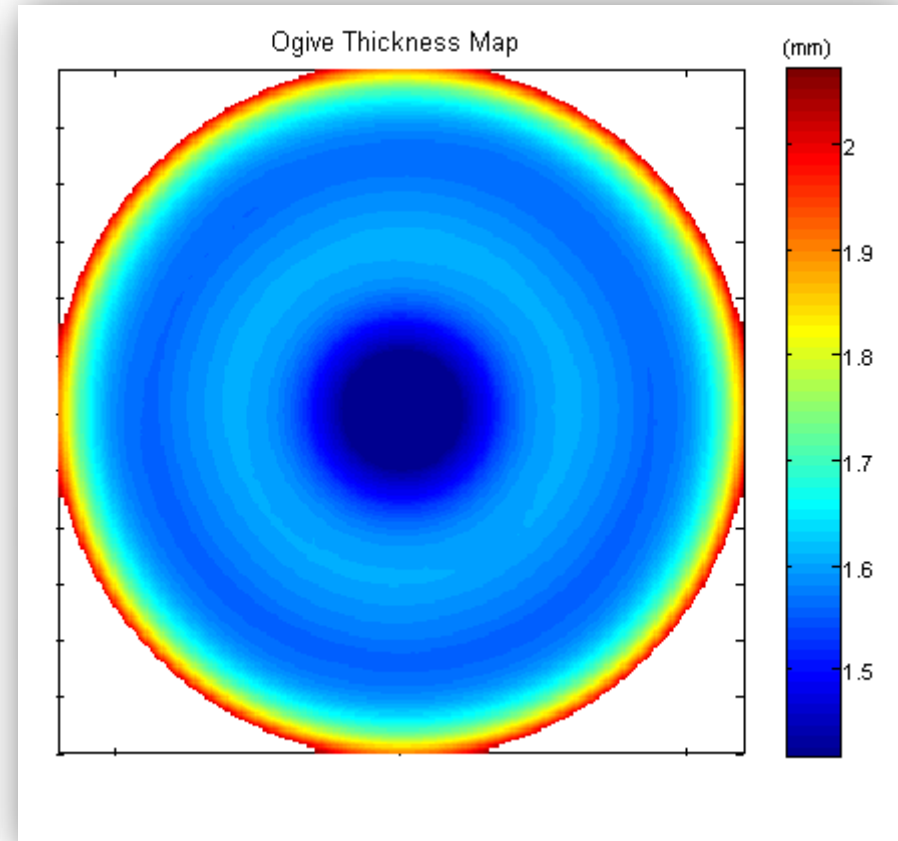
Note Grinding Fixture Features

Ogive Thickness Result

Isometric view of thickness map

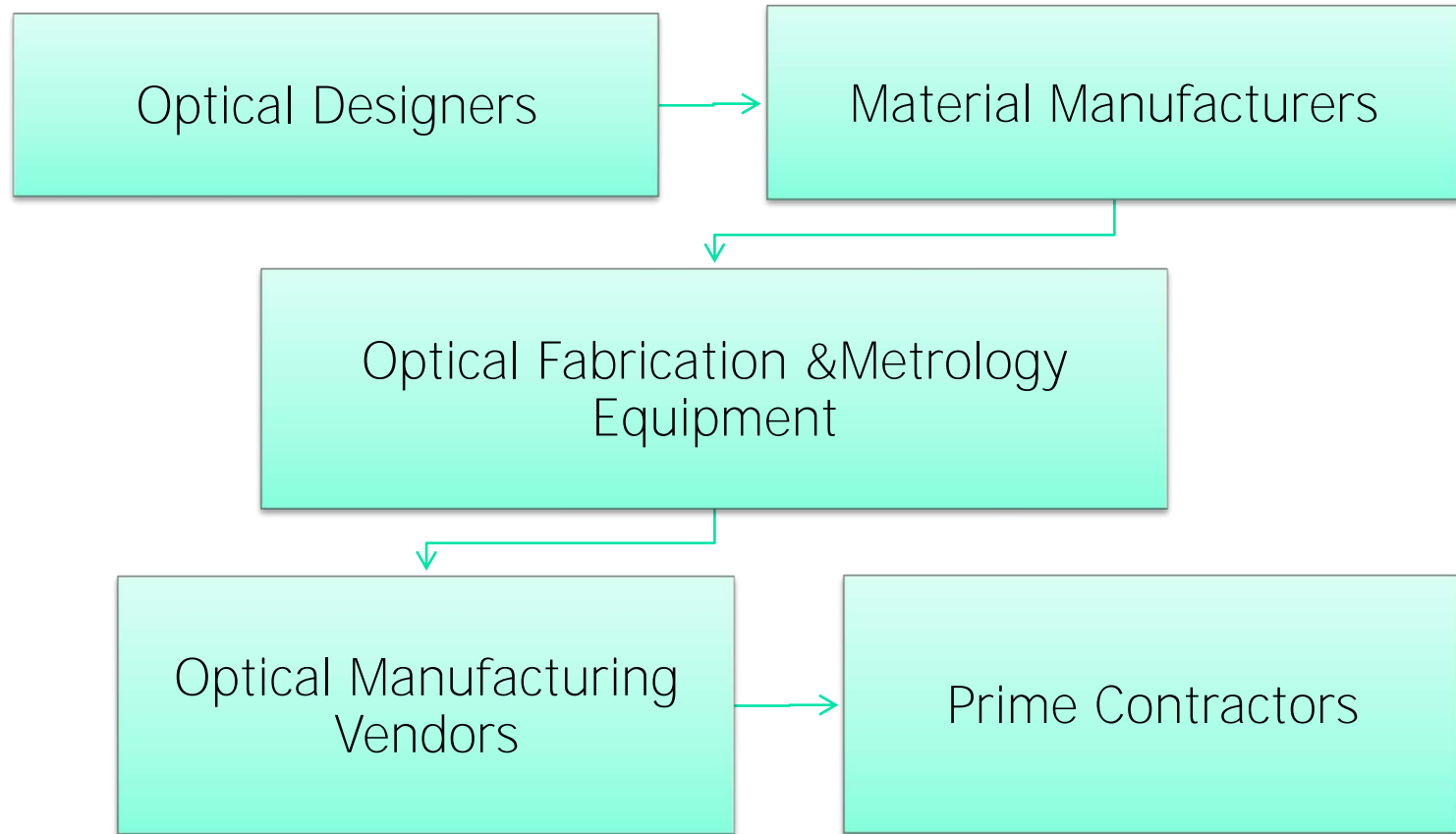


Top Down View





Collaborative Cost Optimization

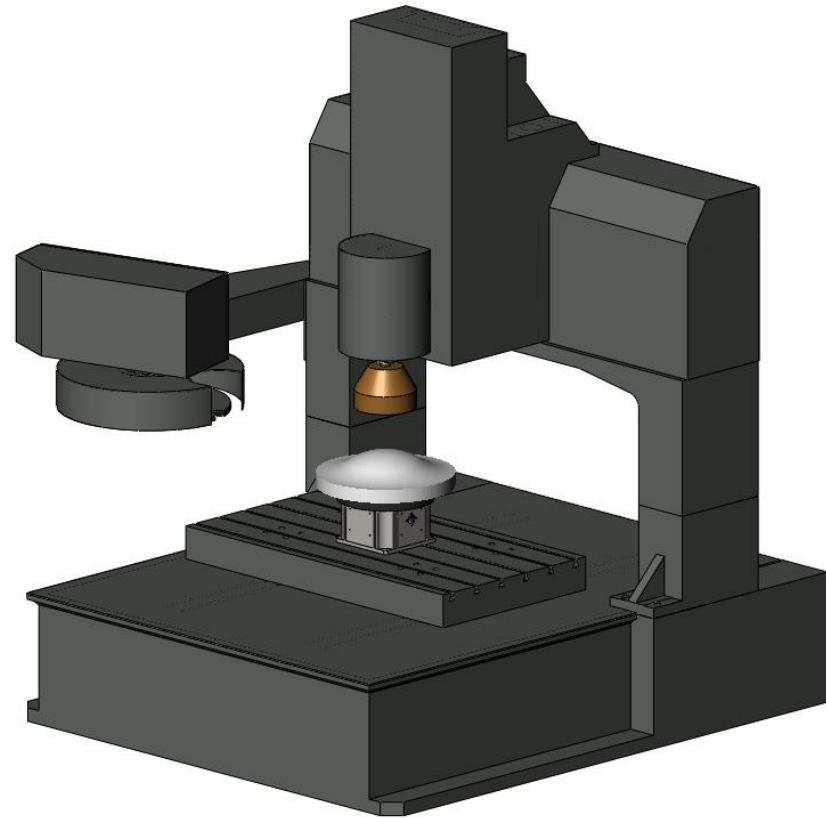




SXL & UFF 500 Optical Fabrication Center

Online in July 2010

- Workpiece Diameter Range of 10-500mm, max weight of 170 kg
- Work Spindle 1-250 rpm
- Tool Spindle 100-12,000 rpm
- Quickchange Tooling
- Vacuum Workholding
- **48" x 28" x 20" XYZ Axes travels**
- B-Axis $\pm 90^\circ$, C-Axis 0° to 360°
- Automatic Tool Changer
- Tool/Workpiece Probe
- User Friendly Operator Screens
- Built in Electronic Spherometer
- Ethernet communications
- Fagor 8070 5-axis CNC Control





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